AD-A253 274

PL-TR-92-2036

# APPLICATION OF THE THEORY OF WAVE PROPAGATION THROUGH RANDOM MEDIA TO PHASE AND AMPLITUDE FLUCTUATIONS OF SEISMIC P-WAVES


Stanley M. Flatté

University of California, Santa Cruz
1156 High Street
Santa Cruz, CA 95064




10 January 1992

Final Report
1 June 1989-31 March 1992

Approved for public release; distribution unlimited

PHILLIPS LABORATORY
AIR FORCE SYSTEMS COMMAND
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

SPONSORED BY
Defense Advanced Research Projects Agency
Nuclear Monitoring Research Office
ARPA ORDER NO. 5307

MONITORED BY
Phillips Laboratory
Contract F19628-89-K-0027

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

This technical report has been reviewed and is approved for publication.

JAMES F. LEWKOWICZ
Contract Manager
Solid Earth Geophysics Branch
Earth Sciences Division

JAMES F. LEWKOWICZ
Branch Chief
Solid Earth Geophysics Branch
Earth Sciences Division

DONALD H. ECKHARDT, Director
Earth Sciences Division

This report has been reviewed by the ESD Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS).

Qualified requestors may obtain additional copies from the Defense Technical Information Center. All others should apply to the National Technical Information Service.

If your address has changed, or if you wish to be removed from the mailing list, or if the addressee is no longer employed by your organization, please notify PL/IMA, Hanscom AFB, MA 01731-5000. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE** 1/10/92

**3. REPORT TYPE AND DATES COVERED** Final Report 6/1/89-3/31/92

**4. TITLE AND SUBTITLE**
Application of the Theory of Wave Propagation Through Random Media to Phase and Amplitude Fluctuations of Seismic P-Waves

**5. FUNDING NUMBERS**
PE:61101E
PR9A10 TADA WU AC
F19628-89-K-0027

**6. AUTHOR(S)**
Dr. Stanley M. Flatté

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
The Regents of the University of California, Santa Cruz
1156 High Street
Santa Cruz, CA 95064

**8. PERFORMING ORGANIZATION REPORT NUMBER**
UCSC-1992001

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

| | |
|---|---|
| Office of Naval Research | Phillips Laboratory |
| 202 McCullough | Contract Manager: James Lewkowicz/GPEH |
| Stanford University | Hanscom AFB, MA 01731-5000 |
| Stanford, CA 95305-4055 | Sponsoring |
| Monitoring | |

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
PL-TR-92-2036

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

Statistical descriptions of variations in seismic-wave velocity in the Earth are related to observations in phase, travel-time, and amplitude fluctuations of seismic-wave signals received at teleseismic and regional distances. Results were obtained by analysis of NORESS and NORSAR data, by stochastic tomography techniques and by numerical simulation. Combination of NORESS and NORSAR data has led to a more highly resolved Transverse Coherence Function of travel time, confirming the Flatte-Wu (FW) model of heterogeneities under NORSAR. Nonlinear inversion applied to NORSAR data has also verified the FW model parameters. Work to compare the FW stochastic model with deterministic heterogeneity models is in progress. Attempts to understand regional propagation by the same techniques have been unsuccessfull due to inability to identify high-frequency crustal propagation paths for regional ranges. Numerical simulation of fluctuations from a point source have verified models of turbulence (applied to the atmosphere).

**14. SUBJECT TERMS**
teleseism, heterogeneities, random media, P-waves, NORSAR

**15. NUMBER OF PAGES** 28

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| unclassified | unclassified | unclassified | SAR |

CONTENTS

## Objective

The long-term objective of this work is to develop a quantitative understanding of the fluctuations in phase and amplitude of seismic wave propagation due to kilometer-scale variations in wave velocity within the earth. The theoretical approach is to describe these variations in a statistical way: in particular to consider the variations as represented by a spectrum that depends on depth, and may depend on geographical location. Data that are relevant to this approach include wave-forms with frequency content above one Hertz received on seismic arrays or on world-wide networks. Relatively high-frequency data is desirable because the ability to discriminate small structure is dependent on the wave having relatively short wavelength. Seismic arrays whose elements are spaced in the kilometers to tens-of-kilometers regime provide analysing power in that regime. Arrays with larger spacing, such as world-wide networks, can still probe small scales if the various available sources have separations in the above range; this can occur for earthquakes in active regions, or for nuclear explosions distributed within test sites.

A realistic understanding of the small-scale structure in the earth is important to fundamental geophysics because it affects our understanding of the fundamental dynamical processes in the earth. Mantle convection, chemical differentiation, fluid permeation, subduction-zone dynamics, and crack formation all will have their effects on small-scale structure, so that creation of more sophisticated theories of these processes will influence, and will be influenced by, our understanding of small-scale structure.

It is not likely that the seismological community will ever have a complete map of inhomogeneities in the earth down to kilometer scales. Therefore we will not be able to completely predict travel-time and amplitude fluctuations for a source-receiver geometry that is even a few kilometers different from previously measured situations. If we have a realistic statistical picture of the small-scale structure in wave-speed within the earth, then the theory of wave propagation through random media (WPRM) can be used to predict the scale and strength of travel-time and amplitude fluctuations due to earth structure. This information can then be used to calculate the accuracy of yield estimates and detection thresholds based on seismic information from an arbitrary array of seismometers, with *a priori* knowledge of results from nearby explosions or earthquakes. Furthermore, this knowledge can be used to design arrays in an optimal fashion to deal with random earth structure.

**Accomplishments**

Statistical descriptions of variations in seismic-wave velocity in the earth are related to observations in phase, travel-time, and amplitude fluctuations of seismic-wave signals received at teleseismic and regional distances. Results were obtained by analysis of NORESS and NORSAR teleseismic and regional data, by stochastic tomography techniques, and by numerical simulation.

Reviews of our previous work were published near the beginning of this contract period. The review of heterogenieities at the core-mantle boundary [Bataille, Wu, and Flatté, 1990] showed that the data (such as PKP precursors) can be explained by CMB topographical height variability of about 200 meters and horizontal scale of a few tens of kilometers. The review of heterogeneities under NORSAR [Wu and Flatté, 1990] confirmed the Flatté-Wu (FW) model of a power-law spectrum of heterogeneities with a few percent rms variability extending down to depths of 250 km.

The original publication of the FW model involved a trial and error method of obtaining model parameters. We have carried out a nonlinear inversion procedure to determine the parameters of the FW model more precisely, and to determine uncertainties in those parameters [Flatté, Wu, and Shen, 1991]. The inversion has verified the trial-and-error parameters, and has shown that the uncertainties are relatively small on the parameters of the model, such as the power-law index and the depth to which the heterogeneities extend,

One limitation of the data that were used in the work that determined the FW model was the separation of the seismic stations on the surface of the earth. The data from subarray averages was used, which meant that the smallest transverse separation available for the transverse coherence functions (TCFs) was about 15 km. We have used individual station waveforms from about 60 events recorded simultaneously at NORSAR and NORESS to determine the TCF of travel time at separations from a few hundred meters to 80 km [Flatté and Xie, 1991]. A copy of this preprint is included in this final report. The result of this work is a further verification of the FW model. The information from NORESS turns out to be confined to determining the tilt of the wavefront across this 3-km-diameter array; no smaller-scale fluctuations are detectable. The information contained in the TCF between separations of a few hundred meters and 15 km is in fact measuring heterogeneities in the earth of a few kilometers in size or greater. The reason that smaller heterogeneities are not relevant is that the frequency band of significant energy (1-3 Hz) has wavelengths of 2-6 km, and the forward propagation of these wavelengths are not sensitive to heterogeneities smaller than about 3 km.

A limitation of the stochastic tomography technique used to determine the FW model lies in the specific data used to compare with the model. The transverse and angular coherence functions (TCFs and ACFs) are not a complete representation of the information contained in the arrival times and intensities of each event at each seismometer. In order to increase the amount of information in the statistical coherence functions to be utilized in tomographic inversions, we have defined a new more complete set of coherence functions, called the Joint Transverse and Angular Coherence Functions [Wu and Xie, 1991]. Work still needs to be done to use these new coherence functions in a tomographic inversion.

Many workers have attempted deterministic tomography fits to travel-time anomalies at NORSAR. We have embarked on a program to compare the results of deterministic tomography with those of stochastic tomography [Zhang, Xie, and Flatté, 1991]. We have taken the velocity fluctuations of the deterministic models as measurements in three-dimensional space, we have determined the spectra of those heterogeneities, and we have compared those spectra with the FW model. The main result of our work to date is an understanding that both the deterministic and stochastic models lack resolution in the vertical. This lack of resolution is manifest in the formulation of the stochastic model, but it has been hidden in the deterministic models, because of the specific choices made as to layer thickness and total thickness of the region of allowed heterogeneity (e.g. 100 km, or 200 km). With that understanding, it should be possible to determine the anisotropy ratio of the FW spectrum from the deterministic-stochastic comparison, at least in the large-scale end of the spectrum.

We have expended a great deal of effort in a program to apply the same stochastic analysis to regional propagation data as we have used for teleseismic events. Our efforts have been presented in several seismology meetings. We have utilized data from NORESS and ARCESS arrays for events in the distance range of several hundred kilometers. The success of this program depends upon identifying bundles of energy that travel along reasonably well-defined paths within the crust: for example, with a single reflection from the MOHO. Unfortunately, it has become evident that such well-defined ray paths are seldom observable beyond the range of 100 km. As a result, very little progress has been made.

Finally, the FW model parameters have been determined by use of a specific assumption about wave propagation behavior; that is, that the data being used have remained in the weak-fluctuation regime. The validity requirement for this assumption has been validated. However, it has been shown that the use of higher-frequency information will require the relaxation of this assumption; in other words, strong-fluctuation theory must be used.

Despite much effort to develop analytical approaches to the strong-fluctuation regime, no such approach has emerged that has the capability of being used in an inversion scheme. The only reliable method of comparing with experimental observations of waves in random media has been developed by the P.I. and collaborators; it is the use of the parabolic approximation in direct numerical simulations. A major breakthrough in this area was achieved in this contract period with the successful comparison with laser propagation through atmospheric turbulence [Martin and Flatte, 1990]. This work showed that the standard assumptions about the spectral behavior of turbulence, combined with the parabolic equation, have all the physics of importance in understanding extensive aspects of the observed fluctuations of intensity at a receiver. These aspects include the variance and the probability distribution of intensity. Spatial patterns of intensity are also predictable by numerical simulation, and have the right qualitative appearance.

The availability of the technique of numerical simulation should allow high-frequency seismic data to be compared with model heterogeneities without the assumption of weak fluctuations.

**Publications Resulting From This Contract**


1. R.S. Wu, "Seismic wave scattering," in *Encyclopedia of Geophysics*, ed. D. James, pp. 1166-1187, Van Nostrand Reinhold and Co., 1989 .

2. R.S. Wu, "Imaging principle of randomly heterogeneous medium by transmitted waves," in *Geophysics in China in the Eighties*, , pp. 360-378, Academic Book and Periodicals Press, Beijing, 1989.

3. K. Bataille, R.S. Wu, and S.M. Flatté, "Inhomogeneities near the core-mantle boundary from scattered waves: A review," *PAGEOPH*, vol. 132, pp. 151-173, 1990.

4. R.S. Wu and S.M. Flatté, "Transmission fluctuations across an array and heterogeneities in the crust and upper mantle," *PAGEOPH*, vol. 132, pp. 175-196, 1990.

5. J.M. Martin and S.M. Flatté, "Simulation of point-source scintillation in three-dimensional random media," *J. Opt. Soc. Am. A*, vol. 7, pp. 838-837, 1990.

6. R.S. Wu, "Recent progress in the research of seismic wave scattering," *Acta Geophysica Sinica*, vol. 33, pp. 349-353, 1990.

7. S.M. Flatté, R.S. Wu, and Z.K. Shen, "Nonlinear inversion of phase and amplitude coherence functions at NORSAR for a model of nonuniform heterogeneities," *Geophys. Res. Lett.*, vol. 18, pp. 1269-1272, 1991.

8. R.S. Wu and X.B. Xie, "Numerical test of stochastic tomography," *Phys. Earth Plenet. Inter.*, vol. 67, pp. 180-193, 1991.

9. S.M. Flatté and X.B. Xie, "The transverse coherence function at NORSAR over a wide range of separations," *submitted to Geophys. Res. Lett.*, December 1991.

10. T.R. Zhang, X.B. Xie, and S.M. Flatté, "Comparison between the stochastic and deterministic heterogeneity models at NORSAR," *Geophys. Res. Lett., in preparation*, December 1991.

## Conferences Attended

The principal investigator attended the following meetings during the contract period:

American Geophysical Union Meeting in San Francisco, December, 1989. A talk on regional propagation was given.

Seismological Society of America Meeting, Santa Cruz, May, 1990. An invited talk on statistical models of heterogeneities was given.

DARPA Seismic Research Symposium, Key West, September, 1990. A talk on the combination of NORESS and NORSAR data was presented.

Seismological Society of America Meeting, San Francisco, March, 1991. A talk on statistical models of heterogeneities was given.

DARPA Seismic Research Symposium, Keystone, Colorado, November, 1991. A poster on the combination of NORESS and NORSAR data was presented.

American Geophysical Union Meeting in San Francisco, December, 1991. Posters on combining NORESS and NORSAR data and on comparing deterministic and statistical models of heterogeneities were given.

## THE TRANSVERSE COHERENCE FUNCTION AT NORSAR OVER A WIDE RANGE OF SEPARATIONS

Stanley M. Flatté and Xiao-Bi Xie
Institute of Tectonics, University of California, Santa Cruz

*Abstract.* We have used data from the 80-km-diameter NORSAR array and the 3-km-diameter NORESS array to determine the Transverse Coherence Function (TCF) of arrival time for spatial separations ranging from a few hundred meters to 80 km. To accomplish our objective, we have devised a method to combine data from arrays of different aperture. The procedure is based on information about rms fluctuations and rms tilts on each array. Synthetic fluctuation fields with different statistical properties were generated to test the combination method. Our results for the TCF from NORSAR and NORESS are in reasonable agreement with the predictions of the Flatté-Wu model of heterogeneities under NORSAR.

Keywords: coherence function, array aperture, lithospheric heterogeneity, NORSAR

### 1. Introduction

During the last 25 years a number of seismic arrays have been installed globally and their data have been widely used to investigate the structure under these arrays. From the stochastic point of view, the structures are represented by a statistical model and a few statistical parameters are used to describe the properties of the medium (e.g., Aki, 1973, Capon, 1974, Capon and Berteussen, 1974, Berteussen et al, 1975a, b, Flatté and Wu 1988, Flatté et al 1991). These parameters include rms velocity fluctuations, correlation distance of the inhomogeneities or the power spectrum of the inhomogeneities, etc.

Inhomogeneities in the crust and mantle can result from different geological structures, and their scales can range from grain size to continental scale. In other words, the inhomogeneities are very broadband in the spatial wavenumber domain. But seismic observations which carry information about the inhomogeneities (e.g., travel-time fluctuations, amplitude fluctuations and various kind of coherence functions, etc.) are band limited because of two effects: first, the finite wavelength of the seismic waves, and second, the size of the real array and minimum sensor separations. For example, the studies cited above use the NORSAR array whose original diameter was 110 km, whose present diameter is 80 km, and whose minimum sensor separation is about 3 km (See Figure 1). Those studies used teleseismic waves with wavelength in the 3-6 km regime. Thus the scale lengths that were studied range from about 3 km to 100 km. A much smaller array (NORESS) is now in operation in the vicinity of NORSAR, with 3-km diameter and minimum sensor separation of a few hundred meters. It is the purpose of our work to use the NORESS data to extend our knowledge of the TCF at NORSAR down to scales less than 3 km, and to determine how that knowledge affects our understanding of the statistical structure of seismic wavespeed.

If we used the data at NORESS independently, the obtained statistical structure of the inhomogeneities would be distorted because we would have no information about fluctuations with scales larger than 3 km. But we do have simultaneous larger-scale information from the larger, coarser NORSAR array. We have developed a special technique to combine data from large-scale, coarse arrays with that from small-scale, fine arrays in order to construct a comprehensive coherence function. We have tested our technique using synthetic random fields with various statistical properties. Finally, real data from the NORSAR area are investigated with this technique. Transverse coherence functions, rms travel-time fluctuations and slowness variations from different arrays are used to create a comprehensive TCF of travel time. This comprehensive TCF is compatible with the inhomogeneity model previously suggested by Flatté and Wu (1988) and Flatté et al (1991).

It must be noted that although data from separations down to a few hundred meters are used in our analysis, we are still restricted in our view of small-scale heterogeneities because of the finite wavelength of the seismic waves. The wavelength limitation is due to the requirement of significant energy observation for teleseismic events, which in our case is 1-3 Hz, or 2-6-km wavelength. Because we are observing forward propagating waves with these wavelengths, the TCF of travel time we observe even at separations of a few hundred meters is controlled by heterogeneities of at least 2-km size (the cutoff is more likely to be in the regime of 3-5 km). In order to observe heterogeneities of significantly smaller size with NORESS, we would have to have events with significant energy in much higher frequency intervals.

## 2. Transverse Coherence Functions and the Effects of Array Size

Theoretically the transverse coherence function (TCF) is calculated from a fluctuation field in an infinite domain, but any actual observation system is finite in the horizontal. Figure 2 schematically shows the fluctuation observations from real arrays, where curve $t(x)$ is the travel time advance (or similarly logarithmic amplitude) that should be observed on the earth's surface. Travel-time data sampled by an array are fitted with a plane wavefront by a least-squares method; after subtracting the fitted plane-wave arrival time, we obtain the travel-time fluctuation. The TCF of travel-time is defined as

$$f(\rho) = \langle t(x)t(x+\rho)\rangle / \langle t^2\rangle \tag{1}$$

where $\rho$ is the transverse separation and $\langle\ \rangle$ represents an ensemble average which we realize by averaging over transverse position $x$.

The problem is to use independent observations on a smaller fine-scale array to find the TCF at small separations. The following formula can be derived connecting the coherence functions and various mean-square fluctuation measurements:

$$\langle t_L^2\rangle\left[1 - f_L(\rho)\right] = \langle t_S^2\rangle\left[1 - f_S(\rho)\right] + \frac{1}{2}\langle\delta u^2\rangle\rho^2 \tag{2}$$

where $f_L(\rho)$ and $f_S(\rho)$ are coherence functions obtained from the large and small array respectively, $\langle t_L^2\rangle$ and $\langle t_S^2\rangle$ are mean square fluctuations for the large and the small arrays, and $\langle\delta u^2\rangle$ is the mean square slowness fluctuation of the small array relative to the large array. The $\langle\delta u^2\rangle$ term dominates if the small array is very much smaller than the large array, while it is unimportant if the small array is very close to the size of the large array. Once the mean-square quantities are obtained, $f_S(\rho)$ can be corrected to $f_L(\rho)$ or vice versa. Thus, by combining different observations (mean square fluctuations, mean square tilt, coherence functions etc.) from arrays of different sizes, we can construct a comprehensive coherence function, $f_L(\rho)$, for which the coherence at small values of $\rho$ can be obtained from the data of a small array. Of course we still can not obtain a coherence function at scales beyond the largest array being used.

The derivation of Eq (2) requires more space than available here, but can be briefly described as follows. The difference between the travel-time fluctuations in a large and small array can be expressed as a difference between the plane-wave fits to each array:

$$t_L(x) - t_S(x) = t_0 + \delta u \cdot x \tag{3}$$

where $t_0$ and $\delta u$ are random variables that are independent of $x$, and the mean values $\langle t_0 \rangle$ and $\langle \delta u \rangle$ are both zero. Eq. (2) then follows from Eqs. (1) and (3), although the derivation requires extensive statistical algebra, and care in treating the differences between the variances of the fluctuations in the large and small arrays.

## 3. Analysis of Synthetic Fluctuations

To examine Eq. (1), numerical tests were carried out. Two-dimensional random fields with two types of coherence functions were used: Gaussian $exp(-\rho^2/a^2)$ and modified Bessel function $K_0(\rho/a)$, where $a$ is the characteristic scale of the random field. Following Frankel (1989), we call these random fields Gaussian and self-similar, respectively. A Gaussian random field is dominated by large-scale fluctuations while a self-similar field is more like a broad-band random field.

We have verified that Eq. (1) can be used to obtain a corrected TCF. Figure 3a shows uncorrected TCFs obtained with various window sizes within a self-similar random field. Figure 3b shows the corrected TCFs. Similar results are obtained for a Gaussian coherence function.

## 4. Analysis of the Real Data from the NORSAR Area

We have divided the Norwegian Seismic Array (NORSAR) into several subarrays (Figure 1). It is expected that under NORSAR the statistical properties of the inhomogeneities are relatively homogeneous. Because NORSAR, NORSAR-R, NORSAR-P, and NORESS are located in the same area while their apertures are quite different, they provide us with an appropriate situation in which to apply our correction procedure to obtain a broad-band TCF.

The data used in our coherence analysis include: the P-wave travel-time anomalies at 22 subarrays of NORSAR from beams (Berteussen 1974), travel-time anomalies at 42 stations of NORSAR-R from 62 events and travel time anomalies at 25 stations of NORESS from 57 events. All the above data are band-pass filtered between 1-3 Hz before analysis. For calculating travel-time fluctuations we have used cross-correlation of the initial few seconds of the seismic waveforms of different stations. The arrival-time difference between the two stations is the time lag for maximum cross correlation. For calculating coherence functions we follow the method of Flatté and Wu (1988), in which station-pair data are binned with respect to station transverse separation. For comparison, Figure 3c gives the travel-time TCFs for these arrays. Table 1 lists the rms values of travel-time fluctuations $t_{rms}$, log-amplitude fluctuations $logA_{rms}$ and slowness (tilt) fluctuations $\delta u_{rms}$ for these arrays. Subarray data means the old data used by Flatté and Wu (1988) which are averaged inside each subarray, and station data means more recent data from

NORSAR-R, NORSAR-P and NORESS, which are directly from individual stations. The rms relative slowness $\delta u_{rms}$ between NORSAR-R and NORSAR is calculated from old NORSAR subarray data, $\delta u_{rms}$ between NORSAR-P and NORSAR-R is from individual station data, $\delta u_{rms}$ between NORESS and NORSAR-R is calculated from 58 events which were simultaneously recorded by both arrays. From Figure 3c and Table 1, it is clear that even in the same area, i.e. where the NORSAR array is located, the statistical measurements are quite different for arrays with different apertures, because each array is missing the effects of inhomogeneities with scales larger than the array. For an array even as large as 100 km, it seems its coherence function still has not reached its stable state, indicating that the inhomogeneities contain variations on scales larger than 100 km.

Shown in Figure 3d are the same coherence functions as those in Figure 3c except that they are corrected with Eq. (1). The NORSAR array is chosen as the reference array. The data listed in Table 1 are used as the coefficients in Eq. (1). The variance $\langle \delta u^2 \rangle$ between NORESS and NORSAR is taken as the sum of the variances of the relative slowness of NORSAR-R with respect to NORSAR (from old subarray data) and the relative slowness of NORESS with respect to NORSAR-R (from simultaneously recorded events). Coherence functions from different arrays are in good agreement. Previous work (Flatté and Wu 1988) gave only the coherence functions with a smallest separation of 15 km, which is limited by the separation between subarrays. Here, by combining the observations from individual stations of smaller arrays, the smallest separation for individual points on the coherence function has been reduced to 5 km.

Our analysis of the wavefront across NORESS shows a plane wave within measurement errors, (~10 ms) which means that the only significant measurement from NORESS is the slowness relative to a larger array. Therefore we have used simultaneous events to determine the mean-square slowness variation for NORESS relative to NORSAR-R. The assumption of plane-wave tilts across NORESS combined with this mean-square slowness gives a specific functional form (a parabola) for the TCF at small separations. This measurement from NORESS is indicated by the shaded region (which includes uncertainty) near small separations in Figure 3d. The shape of this parabola depends on both the property of the underlying inhomogeneity and the wave length of the seismic waves used to detect the inhomogeneity. Also shown in this figure is the coherence function calculated from the inhomogeneity model determined by Flatté et al (1991) from data including this TCF with only the points at separations larger than 15 km. The theoretical curve is reasonably consistent with the observations. It must be remarked again that the finite seismic wavelength limits the rapidity with which the TCF can drop near zero separation. Thus heterogeneities of size much smaller than about 3-5 km cannot be seen with this travel-time data. There is a slight dip near a separation of three kilometers in the theoretical curve that is not seen in the observational data. It is likely that this dip is partially an artifact of the sharp cutoff in the model spectrum of heterogeneities at a wavelength of 5.5 km.

## 5. Conclusions

Analysis of both synthetic and real travel-time data show that the array size has a very strong effect on statistical observations of rms fluctuation, rms tilt and coherence analysis. Before giving any geophysical explanation for those observations, the aperture-size effect must be taken into consideration. The correction formula developed in our work can be used to combine the observations from arrays of different sizes. Numerical tests have confirmed this technique. Potentially, this technique allows us to give a unique description of data acquired by arrays of different apertures in the same geographical area. If one makes the assumption of homogeneous statistical behavior within very different geographical regions, then the same technique can be used to combine data from those different regions as well. Although only the TCF of travel-time fluctuation is discussed here, this technique can also be used to deal with TCFs of the amplitude data, or, with slight modification, could be used for angular coherence analysis.

The application of our correction technique to NORSAR and NORESS data has allowed us to evaluate a TCF of travel time with separations ranging from 100 m to 80 km. The resulting TCF is compatible with the inhomogeneity model determined by Flatté et al (1991) in which a 175-km-thick layer near the surface with large- and small-scale heterogeneities is underlain by a 75-km-thick layer of heterogeneities dominated by large scales, possibly representing an upper-mantle boundary layer. The effective heterogeneity scale sizes that contribute to this TCF are in the regime from about 3 km to 80 km, where the smaller-scale limit is caused by the finite seismic wavelength available in these teleseismic data.

*Acknowledgement.* This work was supported by DARPA and Phillips Laboratory. We are grateful for a grant from the W.M. Keck Foundation. We appreciate conversations with Ru-Shan Wu. This is Contribution Number 149 from the Institute of Tectonics.

## References

Aki, K., Christoffersson, A., and Husebye, E. S., 1977. Determination of the three-dimensional seismic structure of the lithosphere, *J. Geophys. Res.*, **82**, 277-296.

Berteussen, K.A., 1974. NORSAR location calibrations and time delay corrections, *NORSAR Sci. Rep. 2-73/74,* National Technical Information Service, Springfield, Va., 1974.

Berteussen, K. A., Christoffersson, A., Husebye, E. S., and Dahle, A., 1975a. Wave scattering theory in analysis of *P* wave anomalies at NORSAR and LASA, *Geophys. J. R. Astron. Soc.,* **42,** 403-417.

Berteussen, K. A., Husebye, E. S., Mereu, R. F., and Ram, A., 1975b. quantitative assessment of the crust-upper mantle heterogeneities beneath the Gauribidanur seismic array in southern India, *Earth Planet. Sci. Lett.,* **37,** 326-332.

Capon, J., and Berteussen, K.A., 1974. A random medium analysis of crust and upper mantle structure under NORSAR, *Geophys. Res. Lett.,* **1,** 327-328.

Christoffersson, A., and Husebye, E. S., 1979, On three-dimensional inversion of P wave time residuals: option for geological modeling, *J. Geophys. Res.*, **84,** 6168- 6176.

Flatté , S.M., and Wu, R.S., 1988. Small scale structure in the lithosphere and asthenosphere deduced from arrival time and amplitude fluctuations at NORSAR, *J. Geophys. Res.,* **93:** 6601-6614.

Flatté , S.M., Wu, R.S., and Shen, Z.K., 1991. Nonlinear inversion of phase and amplitude coherence functions at NORSAR for a model of nonuniform heterogeneities, *Geophys. Res. Lett.,* **18,** 1269-1272.

Frankel, A., 1989. A review of numerical experiments on seismic wave scattering, in *scattering and Attenuation of Seismic Waves, Part II,* Birkhauser Verlag, Boston.

Table 1: Statistical Measurements from Different Arrays

| array | aperture km | sensors/events | $t_{rms}$ sec. | $\log A_{rms}$ | $\delta u_{rms}$ $s \cdot km^{-1}$ | reference |
|---|---|---|---|---|---|---|
| NORSAR | 110 | 22/104 | 0.135* | 0.41 | | Flatté & Wu, 1988 |
| NORSAR | 110 | 22/104 | 0.115 | | | this work (subarray data) |
| NORSAR-R | 80 | 7/62 | 0.064 | | $4.96 \cdot 10^{-3}$ ** | this work (subarray data) |
| NORSAR-R | 80 | 42/62 | 0.058 | 0.42 | | this work (station data) |
| NORSAR-P | 50 | 24/62 | 0.043 | 0.37 | $2.56 \cdot 10^{-4}$ *** | this work (station data) |
| NORESS | 3 | 25/57 | 0.011 | 0.09 | $2.23 \cdot 10^{-2}$ *** | this work (station data) |

*) without subtracting the deterministic part, **) relative to NORSAR, ***) relative to NORSAR-R

# Figure Captions

Fig. 1. Map of array configurations for NORSAR, NORSAR-R, NORSAR-P and NORESS. The apertures of these arrays are about 110 km, 80 km, 50 km and 3 km, respectively.

Fig. 2. Sketch to show the fluctuations obtained from small and large arrays. Curve $t(x)$ is the observed travel time advance, lines $L$ and $S$ are planes fitted to the wave front for large and small arrays; $\mathbf{u}_L$ and $\mathbf{u}_S$ are their normal vectors. The shaded area is the fluctuation obtained with the large array and the double shaded area is the fluctuation obtained with the small array. Note that the fluctuation from a small array tends to be smaller and its tilt tends to be larger than from a large array.

Fig. 3. Transverse coherence functions for (a) synthetic self-similar random fluctuation fields; (b) synthetic data corrected by Eq. (1). The solid lines are from the original random field and successive curves are from spatial windows with sizes of 60, 40, 30, 20, 10 and 6 units, respectively. (c) data from NORSAR/NORESS for the different apertures shown in Figure 1. NORSAR: closed circles; NORSAR-R: closed triangles; NORSAR-P: open triangles; NORESS: no symbol (solid line). Note that although these arrays are located in the same region, their coherence functions show quite different characteristics. (d) The same coherence functions as (c), but after being corrected with Eq. (1). Only the mean-square slowness measurements from the NORESS data are significant, and so the coherence function maps into a parabola that, including uncertainties, is indicated by the shaded region. All the curves are reasonably consistent. The dashed line is the coherence function from the inversion of Flatté et al (1991).

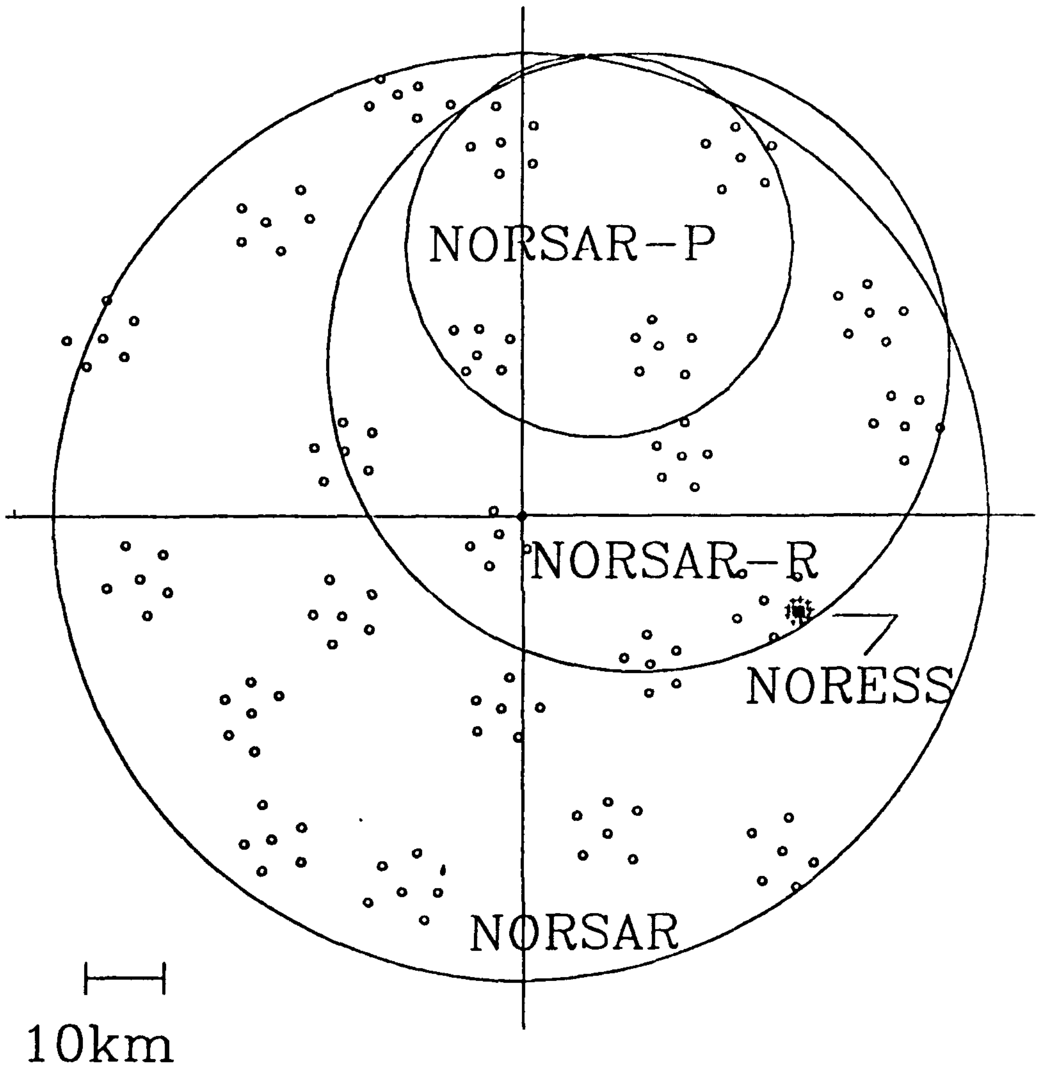


Figure 1

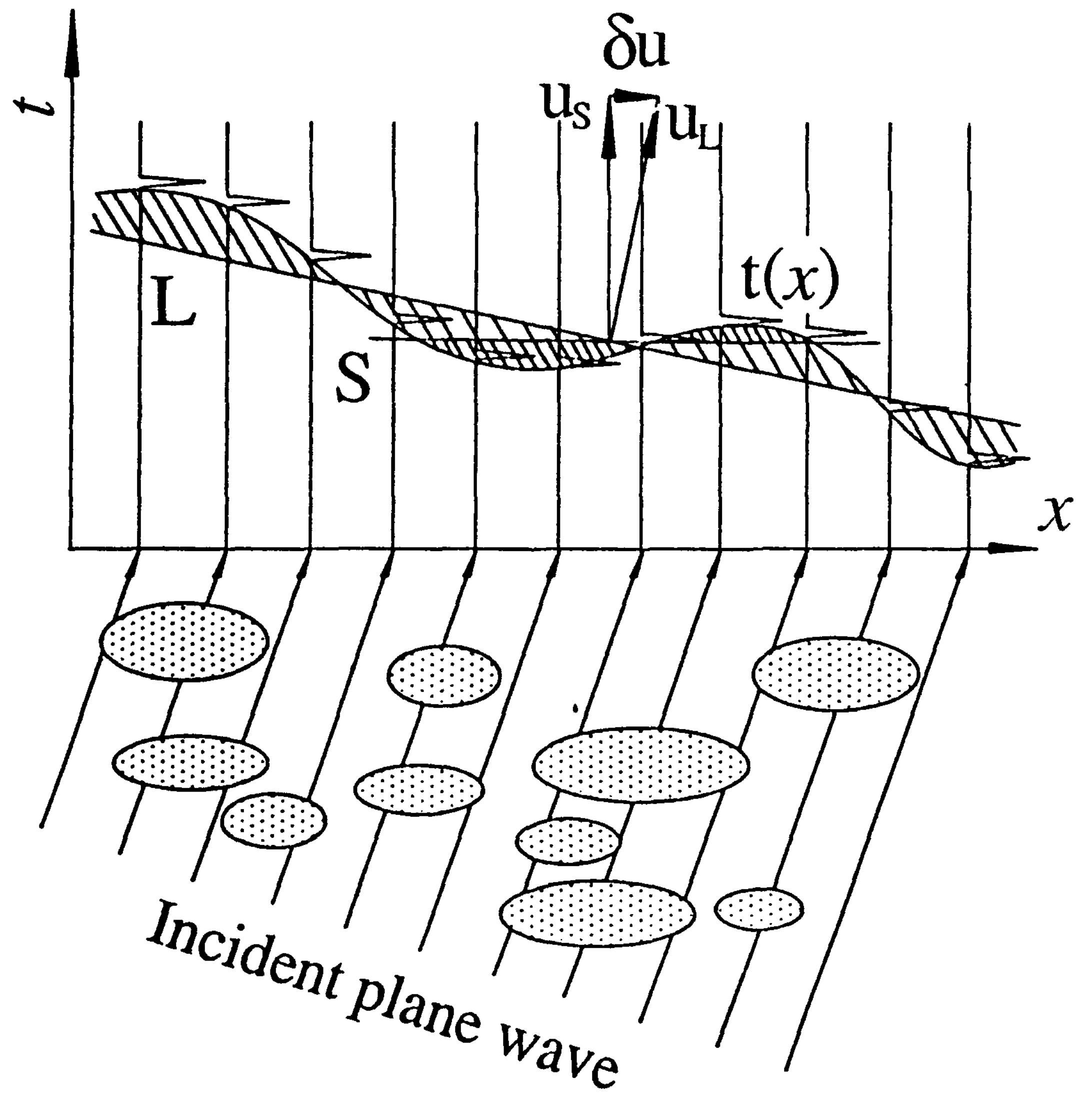


Figure 2

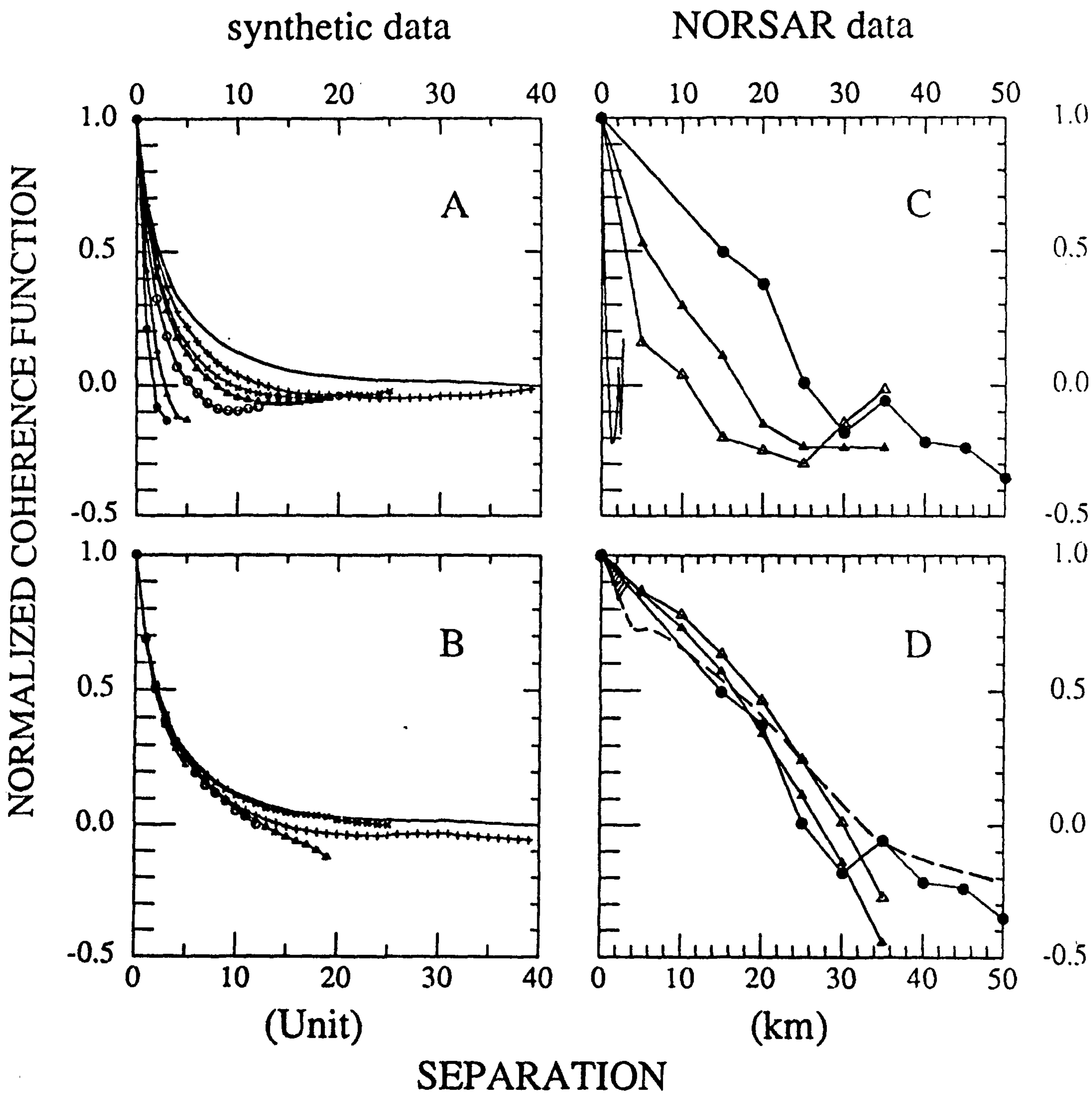
synthetic data
NORSAR data
A
B
C
D
NORMALIZED COHERENCE FUNCTION
1.0
0.5
0.0
-0.5
0
10
20
30
40
50
(Unit)
(km)
SEPARATION

Figure 3

Prof. Thomas Ahrens
Seismological Lab, 252-21
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. Keiiti Aki
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Prof. Shelton Alexander
Geosciences Department
403 Deike Building
The Pennsylvania State University
University Park, PA 16802

Dr. Ralph Alewine, III
DARPA/NMRO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Prof. Charles B. Archambeau
CIRES
University of Colorado
Boulder, CO 80309

Dr. Thomas C. Bache, Jr.
Science Applications Int'l Corp.
10260 Campus Point Drive
San Diego, CA 92121 (2 copies)

Prof. Muawia Barazangi
Institute for the Study of the Continent
Cornell University
Ithaca, NY 14853

Dr. Jeff Barker
Department of Geological Sciences
State University of New York
at Binghamton
Vestal, NY 13901

Dr. Douglas R. Baumgardt
ENSCO, Inc
5400 Port Royal Road
Springfield, VA 22151-2388

Dr. Susan Beck
Department of Geosciences
Building #77
University of Arizona
Tuscon, AZ 85721

Dr. T.J. Bennett
S-CUBED
A Division of Maxwell Laboratories
11800 Sunrise Valley Drive, Suite 1212
Reston, VA 22091

Dr. Robert Blandford
AFTAC/TT, Center for Seismic Studies
1300 North 17th Street
Suite 1450
Arlington, VA 22209-2308

Dr. G.A. Bollinger
Department of Geological Sciences
Virginia Polytechnical Institute
21044 Derring Hall
Blacksburg, VA 24061

Dr. Stephen Bratt
Center for Seismic Studies
1300 North 17th Street
Suite 1450
Arlington, VA 22209-2308

Dr. Lawrence Burdick
Woodward-Clyde Consultants
566 El Dorado Street
Pasadena, CA 91109-3245

Dr. Robert Burridge
Schlumberger-Doll Research Center
Old Quarry Road
Ridgefield, CT 06877

Dr. Jerry Carter
Center for Seismic Studies
1300 North 17th Street
Suite 1450
Arlington, VA 22209-2308

Dr. Eric Chael
Division 9241
Sandia Laboratory
Albuquerque, NM 87185

Prof. Vernon F. Cormier
Department of Geology & Geophysics
U-45, Room 207
University of Connecticut
Storrs, CT 06268

Prof. Steven Day
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

Marvin Denny
U.S. Department of Energy
Office of Arms Control
Washington, DC 20585

Dr. Zoltan Der
ENSCO, Inc.
5400 Port Royal Road
Springfield, VA 22151-2388

Prof. Adam Dziewonski
Hoffman Laboratory, Harvard University
Dept. of Earth Atmos. & Planetary Sciences
20 Oxford Street
Cambridge, MA 02138

Prof. John Ebel
Department of Geology & Geophysics
Boston College
Chestnut Hill, MA 02167

Eric Fielding
SNEE Hall
INSTOC
Cornell University
Ithaca, NY 14853

Dr. Mark D. Fisk
Mission Research Corporation
735 State Street
P.O. Drawer 719
Santa Barbara, CA 93102

Prof Stanley Flatte
Applied Sciences Building
University of California, Santa Cruz
Santa Cruz, CA 95064

Dr. John Foley
NER-Geo Sciences
1100 Crown Colony Drive
Quincy, MA 02169

Prof. Donald Forsyth
Department of Geological Sciences
Brown University
Providence, RI 02912

Dr. Art Frankel
U.S. Geological Survey
922 National Center
Reston, VA 22092

Dr. Cliff Frolich
Institute of Geophysics
8701 North Mopac
Austin, TX 78759

Dr. Holly Given
IGPP, A-025
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093

Dr. Jeffrey W. Given
SAIC
10260 Campus Point Drive
San Diego, CA 92121

Dr. Dale Glover
Defense Intelligence Agency
ATTN: ODT-1B
Washington, DC 20301

Dr. Indra Gupta
Teledyne Geotech
314 Montgomery Street
Alexanderia, VA 22314

Dan N. Hagedon
Pacific Northwest Laboratories
Battelle Boulevard
Richland, WA 99352

Dr. James Hannon
Lawrence Livermore National Laboratory
P.O. Box 808
L-205
Livermore, CA 94550

Dr. Roger Hansen
HQ AFTAC/TTR
Patrick AFB, FL 32925-6001

Prof. David G. Harkrider
Seismological Laboratory
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. Danny Harvey
CIRES
University of Colorado
Boulder, CO 80309

Prof. Donald V. Helmberger
Seismological Laboratory
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. Eugene Herrin
Institute for the Study of Earth and Man
Geophysical Laboratory
Southern Methodist University
Dallas, TX 75275

Prof. Robert B. Herrmann
Department of Earth & Atmospheric Sciences
St. Louis University
St. Louis, MO 63156

Prof. Lane R. Johnson
Seismographic Station
University of California
Berkeley, CA 94720

Prof. Thomas H. Jordan
Department of Earth, Atmospheric & Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

Prof. Alan Kafka
Department of Geology & Geophysics
Boston College
Chestnut Hill, MA 02167

Robert C. Kemerait
ENSCO, Inc.
445 Pineda Court
Melbourne, FL 32940

Dr. Max Koontz
U.S. Dept. of Energy/DP 5
Forrestal Building
1000 Independence Avenue
Washington, DC 20585

Dr. Richard LaCoss
MIT Lincoln Laboratory, M-200B
P.O. Box 73
Lexington, MA 02173-0073

Dr. Fred K. Lamb
University of Illinois at Urbana-Champaign
Department of Physics
1110 West Green Street
Urbana, IL 61801

Prof. Charles A. Langston
Geosciences Department
403 Deike Building
The Pennsylvania State University
University Park, PA 16802

Jim Lawson, Chief Geophysicist
Oklahoma Geological Survey
Oklahoma Geophysical Observatory
P.O. Box 8
Leonard, OK 74043-0008

Prof. Thorne Lay
Institute of Tectonics
Earth Science Board
University of California, Santa Cruz
Santa Cruz, CA 95064

Dr. William Leith
U.S. Geological Survey
Mail Stop 928
Reston, VA 22092

Mr. James F. Lewkowicz
Phillips Laboratory/GPEH
Hanscom AFB, MA 01731-5000( 2 copies)

Mr. Alfred Lieberman
ACDA/VI-OA State Department Building
Room 5726
320-21st Street, NW
Washington, DC 20451

Prof. L. Timothy Long
School of Geophysical Sciences
Georgia Institute of Technology
Atlanta, GA 30332

Dr. Randolph Martin, III
New England Research, Inc.
76 Olcott Drive
White River Junction, VT 05001

Dr. Robert Masse
Denver Federal Building
Box 25046, Mail Stop 967
Denver, CO 80225

Dr. Gary McCartor
Department of Physics
Southern Methodist University
Dallas, TX 75275

Prof. Thomas V. McEvilly
Seismographic Station
University of California
Berkeley, CA 94720

Dr. Art McGarr
U.S. Geological Survey
Mail Stop 977
U.S. Geological Survey
Menlo Park, CA 94025

Dr. Keith L. McLaughlin
S-CUBED
A Division of Maxwell Laboratory
P.O. Box 1620
La Jolla, CA 92038-1620

Stephen Miller & Dr. Alexander Florence
SRI International
333 Ravenswood Avenue
Box AF 116
Menlo Park, CA 94025-3493

Prof. Bernard Minster
IGPP, A-025
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093

Prof. Brian J. Mitchell
Department of Earth & Atmospheric Sciences
St. Louis University
St. Louis, MO 63156

Mr. Jack Murphy
S-CUBED
A Division of Maxwell Laboratory
11800 Sunrise Valley Drive, Suite 1212
Reston, VA 22091 (2 Copies)

Dr. Keith K. Nakanishi
Lawrence Livermore National Laboratory
L-025
P.O. Box 808
Livermore, CA 94550

Dr. Carl Newton
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop C335, Group ESS-3
Los Alamos, NM 87545

Dr. Bao Nguyen
HQ AFTAC/TTR
Patrick AFB, FL 32925-6001

Prof. John A. Orcutt
IGPP, A-025
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093

Prof. Jeffrey Park
Kline Geology Laboratory
P.O. Box 6666
New Haven, CT 06511-8130

Dr. Howard Patton
Lawrence Livermore National Laboratory
L-025
P.O. Box 808
Livermore, CA 94550

Dr. Frank Pilotte
HQ AFTAC/TT
Patrick AFB, FL 32925-6001

Dr. Jay J. Pulli
Radix Systems, Inc.
2 Taft Court, Suite 203
Rockville, MD 20850

Dr. Robert Reinke
ATTN: FCTVTD
Field Command
Defense Nuclear Agency
Kirtland AFB, NM 87115

Prof. Paul G. Richards
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Mr. Wilmer Rivers
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314

Dr. George Rothe
HQ AFTAC/TTR
Patrick AFB, FL 32925-6001

Dr. Alan S. Ryall, Jr.
DARPA/NMRO
3701 North Fairfax Drive
Arlington, VA 22209-1714

Dr. Richard Sailor
TASC, Inc.
55 Walkers Brook Drive
Reading, MA 01867

Prof. Charles G. Sammis
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Prof. Christopher H. Scholz
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, CA 10964

Dr. Susan Schwartz
Institute of Tectonics
1156 High Street
Santa Cruz, CA 95064

Secretary of the Air Force
(SAFRD)
Washington, DC 20330

Office of the Secretary of Defense
DDR&E
Washington, DC 20330

Thomas J. Sereno, Jr.
Science Application Int'l Corp.
10260 Campus Point Drive
San Diego, CA 92121

Dr. Michael Shore
Defense Nuclear Agency/SPSS
6801 Telegraph Road
Alexandria, VA 22310

Dr. Matthew Sibol
Virginia Tech
Seismological Observatory
4044 Derring Hall
Blacksburg, VA 24061-0420

Prof. David G. Simpson
IRIS, Inc.
1616 North Fort Myer Drive
Suite 1440
Arlington, VA 22209

Donald L. Springer
Lawrence Livermore National Laboratory
L-025
P.O. Box 808
Livermore, CA 94550

Dr. Jeffrey Stevens
S-CUBED
A Division of Maxwell Laboratory
P.O. Box 1620
La Jolla, CA 92038-1620

Lt. Col. Jim Stobie
ATTN: AFOSR/NL
Bolling AFB
Washington, DC 20332-6448

Prof. Brian Stump
Institute for the Study of Earth & Man
Geophysical Laboratory
Southern Methodist University
Dallas, TX 75275

Prof. Jeremiah Sullivan
University of Illinois at Urbana-Champaign
Department of Physics
1110 West Green Street
Urbana, IL 61801

Prof. L. Sykes
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Dr. David Taylor
ENSCO, Inc.
445 Pineda Court
Melbourne, FL 32940

Dr. Steven R. Taylor
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop C335
Los Alamos, NM 87545

Prof. Clifford Thurber
University of Wisconsin-Madison
Department of Geology & Geophysics
1215 West Dayton Street
Madison, WS 53706

Prof. M. Nafi Toksoz
Earth Resources Lab
Massachusetts Institute of Technology
42 Carleton Street
Cambridge, MA 02142

Dr. Larry Turnbull
CIA-OSWR/NED
Washington, DC 20505

Dr. Gregory van der Vink
IRIS, Inc.
1616 North Fort Myer Drive
Suite 1440
Arlington, VA 22209

Dr. Karl Veith
EG&G
5211 Auth Road
Suite 240
Suitland, MD 20746

Prof. Terry C. Wallace
Department of Geosciences
Building #77
University of Arizona
Tuscon, AZ 85721

Dr. Thomas Weaver
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop C335
Los Alamos, NM 87545

Dr. William Wortman
Mission Research Corporation
8560 Cinderbed Road
Suite 700
Newington, VA 22122

Prof. Francis T. Wu
Department of Geological Sciences
State University of New York
at Binghamton
Vestal, NY 13901

AFTAC/CA
(STINFO)
Patrick AFB, FL 32925-6001

DARPA/PM
3701 North Fairfax Drive
Arlington, VA 22203-1714

DARPA/RMO/RETRIEVAL
3701 North Fairfax Drive
Arlington, VA 22203-1714

DARPA/RMO/SECURITY OFFICE
3701 North Fairfax Drive
Arlington, VA 22203-1714

HQ DNA
ATTN: Technical Library
Washington, DC 20305

Defense Intelligence Agency
Directorate for Scientific & Technical Intelligence
ATTN: DTIB
Washington, DC 20340-6158

Defense Technical Information Center
Cameron Station
Alexandria, VA 22314 (2 Copies)

TACTEC
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201 (Final Report)

Phillips Laboratory
ATTN: XPG
Hanscom AFB, MA 01731-5000

Phillips Laboratory
ATTN: GPE
Hanscom AFB, MA 01731-5000

Phillips Laboratory
ATTN: TSML
Hanscom AFB, MA 01731-5000

Phillips Laboratory
ATTN: SUL
Kirtland, NM 87117 (2 copies)

Dr. Michel Bouchon
I.R.I.G.M.-B.P. 68
38402 St. Martin D'Heres
Cedex, FRANCE

Dr. Michel Campillo
Observatoire de Grenoble
I.R.I.G.M.-B.P. 53
38041 Grenoble, FRANCE

Dr. Kin Yip Chun
Geophysics Division
Physics Department
University of Toronto
Ontario, CANADA

Prof. Hans-Peter Harjes
Institute for Geophysic
Ruhr University/Bochum
P.O. Box 102148
4630 Bochum 1, GERMANY

Prof. Eystein Husebye
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

David Jepsen
Acting Head, Nuclear Monitoring Section
Bureau of Mineral Resources
Geology and Geophysics
G.P.O. Box 378, Canberra, AUSTRALIA

Ms. Eva Johannisson
Senior Research Officer
National Defense Research Inst.
P.O. Box 27322
S-102 54 Stockholm, SWEDEN

Dr. Peter Marshall
Procurement Executive
Ministry of Defense
Blacknest, Brimpton
Reading FG7-FRS, UNITED KINGDOM

Dr. Bernard Massinon, Dr. Pierre Mechler
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE (2 Copies)

Dr. Svein Mykkeltveit
NTNT/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY (3 Copies)

Prof. Keith Priestley
University of Cambridge
Bullard Labs, Dept. of Earth Sciences
Madingley Rise, Madingley Road
Cambridge CB3 OEZ, ENGLAND

Dr. Jorg Schlittenhardt
Federal Institute for Geosciences & Nat'l Res.
Postfach 510153
D-3000 Hannover 51, GERMANY

Dr. Johannes Schweitzer
Institute of Geophysics
Ruhr University/Bochum
P.O. Box 1102148
4360 Bochum 1, GERMANY